HADRONIC JOURNAL 48, 427 - 438 (2025)
DOI 10.29083/HJ.48.04.2025/SC427

HAWKING PROCESS AND NEGATIVE ENERGY

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Received October 28, 2025

Abstract

Hawking radiation provides a possible mechanism for the production of negative energy. While this negative energy accumulates inside the event horizon, positive energy is radiated from the black hole. The negative energy facilitates a number of physical effects that foster the stability of black holes and wormholes. Negative energy was previously investigated as a consequence of traditionally excluded Feynman diagrams. These diagrams provide a possible theoretical mechanism for the creation of negative energy. An evaluation of the associated amplitudes of these diagrams suggest that light field particles and photons are the dominant component of the Hawking radiation since their amplitudes scale as the reciprocal of the created particle mass.

KEYWORDS: Hawking radiation; black holes; Schwarzschild metric; negative energy creation; and black hole thermodynamics.

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1.0 Introduction

A number of papers address Hawking radiation, associated particle production, and black hole thermodynamics [1-12]. As a prelude to Hawking's radiation assertion, Bekensteing [1] provided essential justification and discussion of a number of similarities between black-hole physics and thermodynamics. Prior to the radiation assertion, Hawking [2] showed that a black hole creates and emits particles (e.g., neutrinos and photons) at a rate consistent with a body having a temperature proportional to the surface gravity of the black hole. Accordingly, as a black hole emits this thermal radiation, it loses mass.

Hawking noted that black holes are not static, but continuously radiate energy [3]. This situation arises from quantum effects in the electromagnetic field of a black hole. According to the uncertainty principle, electromagnetic field particles or photons are not precisely localized. In the vicinity of the black hole horizon, Hawking utilized quantum field theory to describe the properties of photons near the event horizon [3]. Page provided a comprehensive review of Hawking radiation and black hole thermodynamics [4].

As an extension of Hawking's work, Firouzjaee, and Ellis [5] addressed the black hole particle creation probability rate resulting from quantum fluctuations. [5] suggests that the Hawking radiation emission process also occurs for a dynamic black hole when it has a slowly evolving horizon.

Steinhauer [6] noted spontaneous Hawking radiation, stimulated by quantum vacuum fluctuations, resulted from an analogue black hole in an atomic Bose–Einstein condensate. These observations suggest an approximately thermal distribution of Hawking radiation.

Other aspects associated with Hawking radiation and black hole thermodynamics are noted in [7 – 12]. For example, Kolobov et al. [12] noted that Hawking radiation from a black hole is a slowly evolving process, and this condition is required for the correspondence between Hawking and blackbody radiation.

Additional aspects of related cosmology [13-14] and conventional thermodynamics and its applications are provided by Santilli [15-16]. These papers provide supporting commentary regarding the thermodynamic and cosmological basis for the Hawking radiation process.

These various aspects of Hawking radiation and associated black hole thermodynamics are contingent on particle creation near the event horizon. The implications of the creation of negative energy particles [17,18] near the event

horizon, and the connection to traditionally excluded Feynman diagrams are the subject of this paper.

2.0 Theoretical Description of Hawking Radiation

Hawking derived the black hole radiation concept utilizing a rigorous quantum field theory approach [3]. The Hawking radiation concept can also be derived in a somewhat simplified form by considering the implications of the uncertainty relationship [19]

$$\Delta E \, \Delta t \geq \hbar/2 \tag{1}$$

where ΔE is the minimum uncertainty in the created particle energy that resides in a quantum state for a time Δt. As noted in previous publications [17-18], spacetime allows vacuum fluctuations in the electromagnetic fields that produce pairs of particles including photons that are produced at one event location and destroyed at another. The created pairs violate conservation of energy by an amount ΔE unless they exist for less than a time $\Delta t = \hbar/2\Delta E$. In that event, no conservation law is violated. Consistent with quantum field theory, on shell conservation of energy is achieved (at a macroscopic scale), while it is violated off shell (on a quantum level).

Spacetime near the event horizon of a black hole is locally flat, and quantum fluctuations will routinely occur. If a fluctuation produces a photon pair, one has energy E and the other -E. In flat spacetime, the negative energy photons combine with the positive energy ones before the time $\hbar/2E$ elapses. However, if the fluctuation produces a pair just outside the event horizon, a negative energy photon could cross the horizon before the time $\hbar/2E$ elapses. Once inside the black hole, the negative energy photon can move freely.

The following discussion is consistent with the more comprehensive treatment of Schultz [19]. Readers should consult [19] for additional details supporting the Section 2.0 commentary.

Considering the Schwarzschild metric, negative energy is normally excluded because it corresponds to a particle that travels backward in time [19]. Inside the event horizon, an observer going forward in time is traveling in the direction of decreasing r. As an example, select a trajectory characterized by $p^0 = 0$ and $U^0 = 0$, where U is the four velocity and p is the four momentum. Given these conditions and assuming only radial motion, U^r is the only nonzero four-velocity component. The usual normalization condition applies,

$$U \cdot U = -1 \tag{2}$$

and yields the value U^r for the Schwarzschild metric

$$U^r = -\left(\frac{2M}{r} - 1\right)^{1/2} \qquad \text{for } r < 2M \tag{3}$$

where M is the mass in the Schwarzschild metric. U^r is negative because the observer is ingoing. For the condition $-p \cdot U > 0$, any photon orbit is allowed.

Given this condition, consider a zero angular momentum photon that moves radially inside the event horizon. As noted in [19], this photon has energy $E = \pm p^r$, and its energy relative to the observer is

$$-p \cdot U = -g_{rr}\, p^r\, U^r = -\left(\frac{2M}{r} - 1\right)^{-\frac{1}{2}}\, p^r \tag{4}$$

where $g_{rr} = \left(\frac{2M}{r} - 1\right)^{-1}$ for the Schwarzschild metric. This is positive if the photon trajectory is ingoing ($p^r < 0$). However, the aforementioned condition establishes no restrictions on the energy E. Photons can follow null trajectories inside the horizon and can have either sign for E as long as $p^r < 0$.

A fluctuation near the event horizon can create a trajectory in which the positive energy photons move radially outward from the horizon, and can escape to infinity. The negative energy photons can travel inward and remain inside the event horizon.

For this condition, consider the fluctuations in a freely falling inertial reference frame (i.e., one that is locally flat). A frame that is momentarily at rest at the coordinate $r = 2M + \varepsilon$ will fall inward following the trajectory of a particle with zero angular momentum and energy ($\bar{E}$) [19]

$$\bar{E} = \left[1 - \frac{2M}{2M+\varepsilon}\right]^{1/2} \approx \left(\frac{\varepsilon}{2M}\right)^{1/2} \tag{5}$$

The photon reaches the event horizon after a proper time $\Delta\tau$

$$\Delta\tau = -\int_{2M+\varepsilon}^{2M} \left[\frac{2M}{r} - \frac{2M}{2M+\varepsilon}\right]^{-1/2} dr \tag{6}$$

To first order in ε, $\Delta\tau$ is

$$\Delta\tau = 2\,(2M\epsilon)^{1/2} \tag{7}$$

The photon energy Σ in this frame is obtained by setting $\Delta\tau$ equal to the fluctuation time $\hbar/2\Sigma$ derived from the uncertainty relationship

$$\Sigma = \frac{\hbar}{4}\,(2M\epsilon)^{-1/2} \tag{8}$$

In (8), Σ is the energy of the outgoing photon (i.e., the one that reaches infinity) as determined in the local inertial reference frame. The energy of this photon when it reaches infinity is [19]

$$\Sigma = -\vec{p}\cdot\vec{U} \tag{9}$$

where

$$-U_0 = \bar{E} \approx \left(\frac{\varepsilon}{2M}\right)^{1/2} \tag{10}$$

Therefore,

$$\Sigma = -g^{00}\,p_0\,U_0 = g^{00}\,U_0\,E \tag{11}$$

where E is the conserved energy on the photon's trajectory, and is also the energy when the outgoing photon reaches infinity. When g^{00} is evaluated at $2M + \varepsilon$,

$$E = \Sigma\left(\frac{\epsilon}{2M}\right)^{1/2} = \frac{\hbar}{8M} \tag{12}$$

This is the characteristic energy of the photon, independent of its origin, when it escapes from the black hole.

Hawking radiation is significant since it applies to several geometries (i.e., Kerr (rotating) and Schwarzschild (static) black holes). In addition, it connects the negative energy photons inside the event horizon with their positive energy counterparts outside the horizon. Hawking radiation is steady thermal energy created by quantum fluctuations near the horizon.

This result suggest that as positive energy is radiated from the black hole, negative energy accumulates inside the event horizon. The possible consequences of this accumulation of negative energy was noted in previous publications [17,18].

3.0 Implications of Negative Energy

In previous papers [17-18], negative energy was noted to theoretically arise as a consequence of forbidden S2 (Figs, 1 and 2) as well as coupled $S^1 \times S^1$ (Fig, 3) Feynman diagrams. These initial assessments of a Planck-Scale quantum field theory identified three basic Feynman diagrams that could generate negative energies (i.e., vacuum bubbles, closed loops, and coupled single vertex diagrams at the Planck-scale). These diagrams are discussed in detail in Refs, [17-18], and a summary is provided in subsequent commentary.

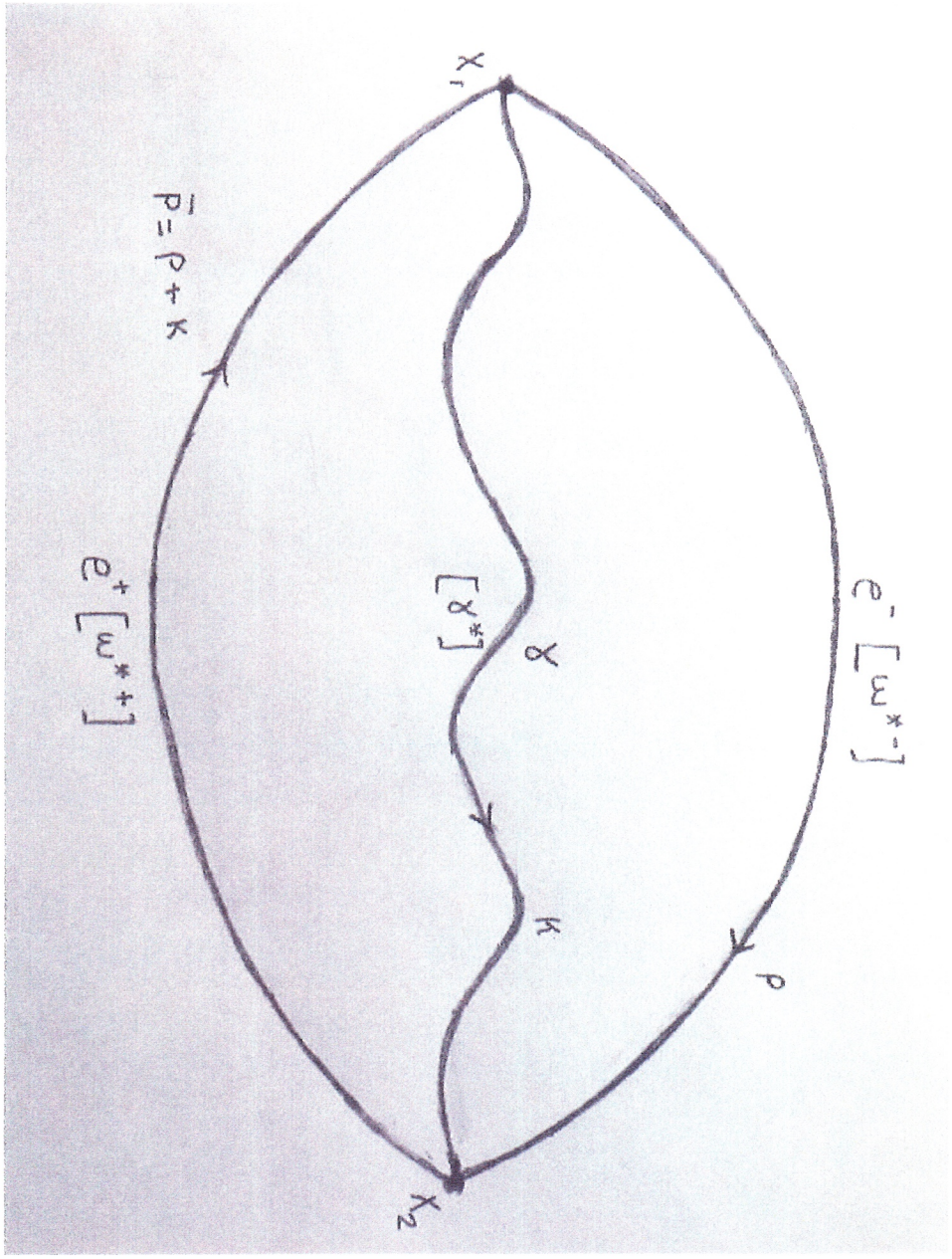

Fig. 1. Vacuum bubble Feynman diagram and the generalized Planck-scale analogue. The S_2 vacuum bubble produces negative energy particles. The terms in brackets refer to particles arising at the Planck-scale. Other quantities (electrons, positrons, and photons) refer to standard QED processes. The two processes illustrated in the figure are separate and distinct with the "*" superscript denoting Planck-scale particles.

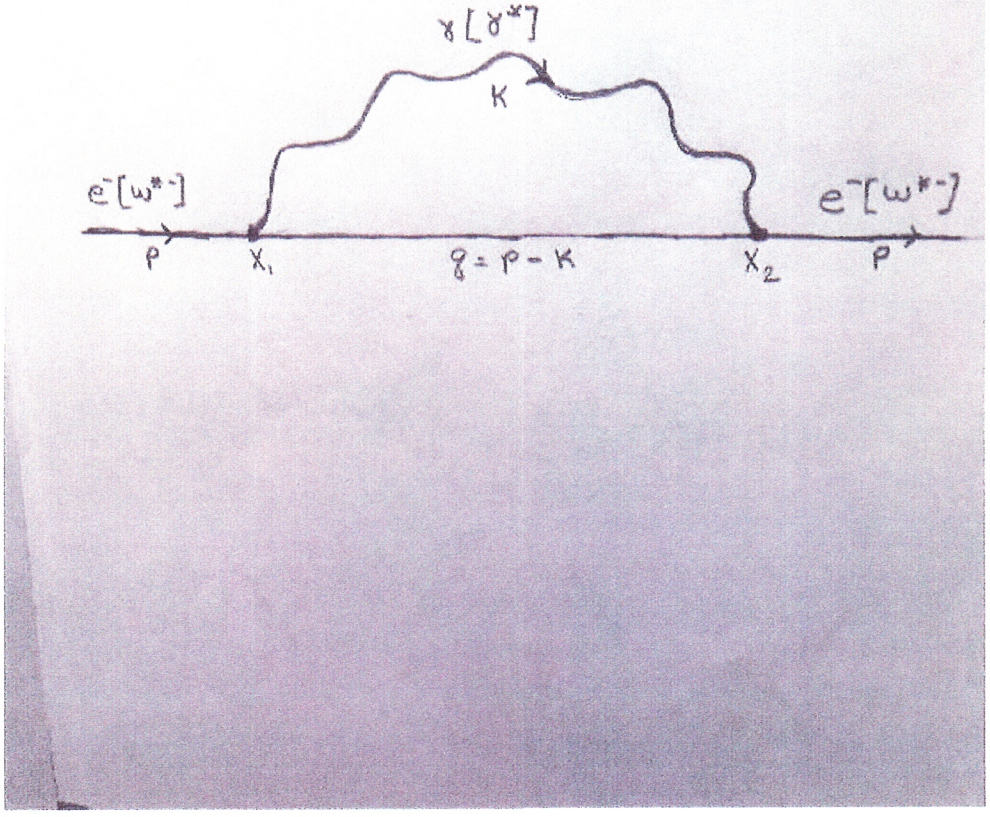

Fig. 2. Closed loop Feynman diagram and the generalized Planck-scale analogue. The S_2 loop diagram produces negative energy particles. The terms in brackets refer to particles arising at the Planck-scale. Other quantities (electrons and photons) refer to standard QED processes. The two processes illustrated in the figure are separate and distinct with the "*" superscript denoting Planck-scale particles.

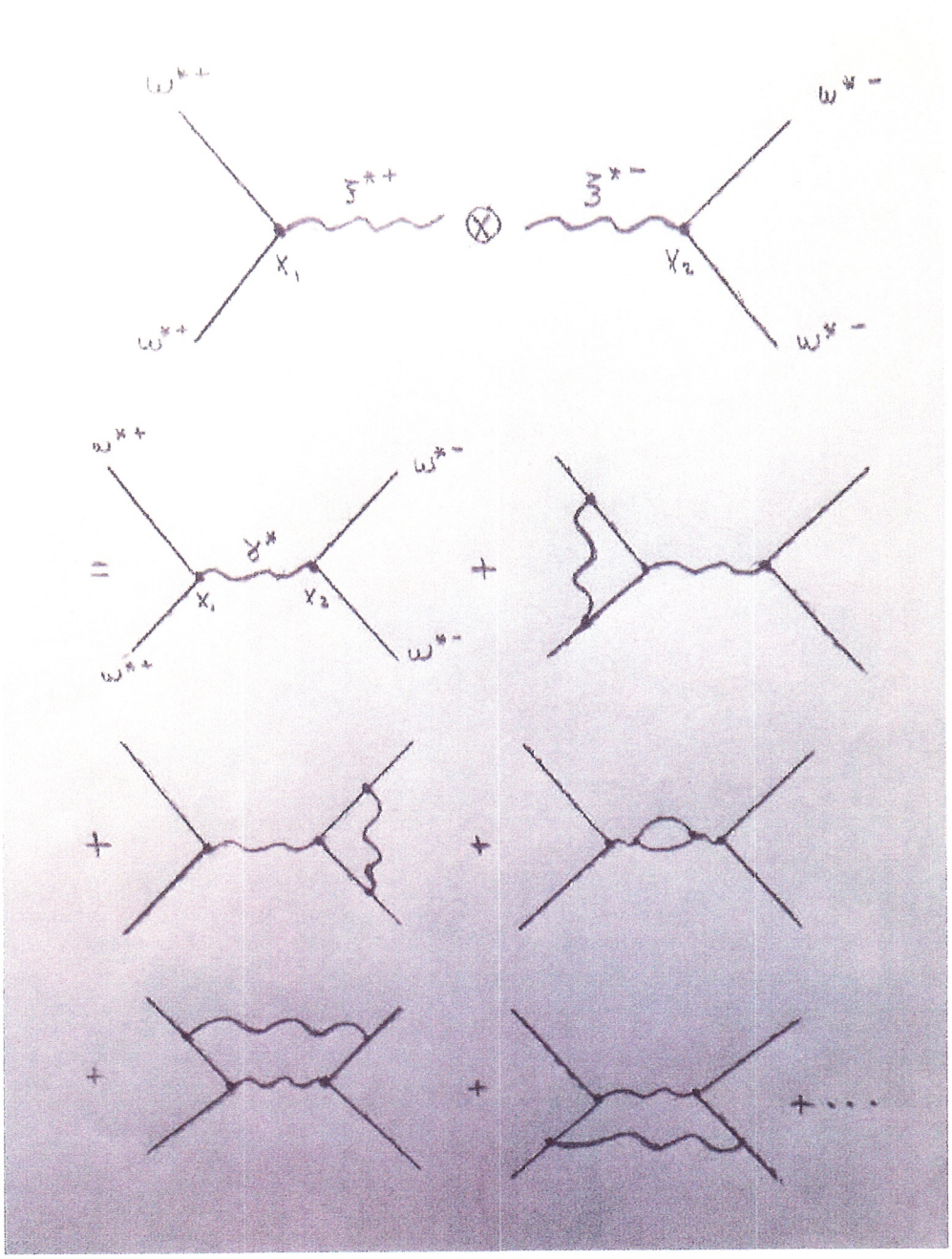

Fig. 3. Two coupled S_1 diagrams that produce positive and negative energy particles. These particles occur at the Planck-scale. The tree level and selected higher order terms are illustrated.

These diagrams were constructed in general without a specific physical context, but the previous discussion suggests that the requisite negative energy can theoretically occur through a vacuum fluctuation near the event horizon of a black hole. Previously, the origin of the negative energy was unspecified [17,18], but the region just outside the event horizon provides a possible physical creation location for the negative energy particles that are part of the Hawking radiation creation process. In addition, these negative energies were previously noted to facilitate a variety of effects including wormhole stability, black hole stability, and creation of new exotic particles [17.18]. As noted in [17-18], these particles could be created from a new class of $S^1 \times S^1$ Feynman diagrams.

The derivation of the resulting amplitudes corresponding to Figs. 1, 2, and 3 were provided in [18] and the results are summarized in subsequent discussion. In evaluating the amplitude of Fig. 1, the following assumptions were utilized: (1) basic Feynman rules are applicable, (2) two-dimensional φ^4 scalar field theory is applicable, (3) light front coordinates are utilized, and (4) QED or an analogous QFT is applicable.

Fig. 1 corresponds to a vacuum bubble with associated amplitude [18]

$$A(\text{Fig.1}) = -\frac{i\lambda^2}{\mu^2}\pi^2 NC \propto \frac{\lambda^2}{\mu^2} \tag{13}$$

where λ is the vertex coupling constant, p and k are the light front momenta defined in Fig. 1, and G(q) and N are defined as

$$G(q) = \frac{i}{q^2 - \mu^2 + i\varepsilon} \tag{14}$$

$$N = \frac{1}{3!}\frac{1}{i(2\pi)^4} \tag{15}$$

In (13-15), μ is the scalar field particle mass, the 1 / 3! is a symmetry factor, and C is a constant (~ 2.3439). The amplitude of Fig. 1 is inversely proportional to the square of the scalar field particle mass.

The amplitude of Fig. 2 corresponds to a closed loop diagram. In [18] it was evaluated assuming that (1) the basic Feynman rules are applicable, (2) two-

dimensional φ^4 scalar field theory is applicable, (3) light front coordinates are utilized, (4) QED or an analogous QFT is applicable, (5) the requisite integrals are evaluated with the cutoff limit $\Lambda \rightarrow \infty$, and (6) the amplitude is evaluated with the $p = 0$ limitation. Given these assumptions, the amplitude of Fig. 2 is

$$A(\text{Fig. 2}) = \left(\frac{i}{16\pi^2}\right)\frac{\lambda^2}{\mu^2}(-2\pi i)\int_{-\infty}^{+\infty} dk^+ \delta(k^+) = \frac{1}{8\pi}\frac{\lambda^2}{\mu^2} \propto \frac{\lambda^2}{\mu^2} \qquad (16)$$

The Fig. 2 amplitude is similar to the Fig. 1 amplitude since both results are proportional to λ^2 / μ^2. This result implies that the amplitudes for Figs. 1 and 2 are governed by the coupling constant λ and the scalar field particle mass μ.

The amplitude of Fig. 3 corresponds to a coupled diagram. In [18] it was evaluated assuming that (1) the basic Feynman rules are applicable, (2) QED or an analogous QFT is applicable, (3) The $m(\gamma^*) >> (p_1 + p_2)^2$ assumption is similar to the Fig. 2 $p = 0$ limitation, and (4) ξ^{*+} and ξ^{*-} annihilate to produce a photon analogue γ^+. For the Hawking radiation process the γ^+ is either a light scalar field particle or photon. Given these assumptions, the amplitude of Fig. 3 is similar to the previous results for the amplitudes for Figs. 1 and 2.

$$A(\text{Fig. 3}) \propto \frac{g^2}{m(\gamma)^2} \rightarrow \frac{\lambda^2}{\mu^2} \qquad (17)$$

where the substitution $g \rightarrow \lambda$ and $m(\gamma) \rightarrow \mu$ is used to facilitate comparison to the Figs. 1 and 2 amplitude results. For all three diagrams, the largest amplitudes are attributed to the smallest field particle masses. This result provides possible insight into the physical characteristics of Hawking radiation, and its relationship to Feynman diagrams that lead to the production of negative energy.

4.0 Emergence of Light Particles

The Fig. 3 Feynman diagram naturally leads to the creation of the Hawking energy photons through the coupled $S^1 \times S^1$ diagrams. Figure 3 implicitly contains two field particles that represent creation and annihilation mechanisms that could create a photon pair near the event horizon. An evaluation of the tree-level coupled diagram and other negative energy diagrams by a number of methods [18], leads to the natural emergence of amplitudes that are enhanced by the creation of low mass field particles or photons.

In [18], the S^1 x S^1 diagrams of Fig. 3 were developed as a theoretical construct to create negative energy photons. The Hawking radiation process provides a context for the possible applicability of these coupled diagrams. The creation of photons derived from these diagrams provides a possible theoretical mechanism for the Hawking radiation process. Therefore, there is a possible relationship between the S^1 x S^1 diagrams, the creation of negative energy particles or photons, and Hawking radiation. This is an important point that possibly links the concept of negative energy, Hawking photons, and unique Feynman diagrams.

5.0 Conclusions

The Hawking radiation process is an important theoretical concept that affects the behavior of black holes. Vacuum fluctuations can create photon pairs. If these pairs are created in proximity to the event horizon, the positive energy photon can escape to infinity while the negative energy photon can travel inside the event horizon and move freely.

The postulated S^1 x S^1 diagrams provide is a theoretical means for the creation of negative energy, and subsequent emission of Hawking radiation. This is an important point that possibly links the concept of negative energy, Hawking radiations, and unique Feynman diagrams.

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